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A TRIDENT SCHOLAR PROJECT REPORT

NO. 167

UPWELLING SOUTHWEST OF ICELAND DUE TO QUASI-GEOSTROPHIC FLOW

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U.S.N.A. - Trident Scholar project report; no. 167 (1990)

UPWELLING SOUTHWEST OF ICELAND DUE TO QUASI-GEOSTROPHIC FLOW

A Trident Scholar Project Report

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ABSTRACT

Investigation of unusual upwelling occurrences southwest of Iceland (64°N, 26°W) suggests causes due to quasi-geostrophic flow over submarine bathymetry. Complex circulation patterns occur in this region and no predominant pattern has been recognized to account for the upwelling. Two submarine canyons are located 30 km northeast of the approximate location of the upwelling center. It is postulated that quasi-geostrophic flow over the canyons and a resulting conservation of potential vorticity is the cause of the upwelling. Satellite imagery, hydrographic data, wind patterns, and mean currents all point to a temperature "doming". This suggests a persistent bottom-generated feature. Submarine bathymetry appears to play the dominant role in the upwelling.

TABLE OF CONTENTS

ILLUSTRATIONS

INTRODUCTION

Study of the processes which shape our world's oceans becomes increasingly more important with greater utilization of their resources. Upwellings occur when deep ocean water rises vertically towards the surface; this phenomenon significantly affects oceanographic conditions. Generally the upwelled water is much colder and richer in nutrients than the water it replaces. Oceanographic upwelling is a relatively slow phenomenon which can occur anywhere but which predominantly takes place along the western margins of continents. The effects of an upwelling can extend out hundreds of miles from the coast. Scientifically, an upwelling is an important oceanic process, because water properties are radically altered at the surface. Cold, nutrient-rich, deep water when moved vertically upward, provides revitalized phytoplankton growth and a subsequent boom in the fish population. With today's highly specialized equipment and technology, the U.S. Navy is realizing the advantages that can be gained by using the ocean environment to operational advantage. Knowledge of water properties, bottom topography, current patterns, and so forth, will especially provide the U.S. with an edge in anti-submarine warfare (ASW).

This study examines unusual oceanographic upwelling occurrences southwest of Iceland. First documented and attributed to shelf-break upwelling by Foerster and Thompson

(1985), investigations of the upwelling suggests a cause due to quasi-geostrophic flow over submarine bathymetry. Two submarine canyons are located approximately 30 km northeast of the upwelling center. Complex current and circulation patterns occur in this region, but no predominant pattern has been recognized to account for the upwelling. The documentation provided by this report seems to point instead to a persistent feature generated by flow over the bottom bathymetry.

Documentation of the feature, using satellite imagery, hydrographic data, wind patterns, mean currents, and results from previous studies, verified the occurrence of a temperature "doming". After verification of the upwelling, the region will be analyzed to provide evidence that the submarine bathymetry plays the dominant role in the upwelling. This project collected, analyzed, and applied data to support an idealized model of quasi-geostrophic flow over topography.

The waters surrounding Iceland have been minimally investigated in the past. More detailed study could benefit the Navy's critical ASW interests in the northern waters. Also, knowledge of the water properties associated with an upwelling could be advantageous for sound propagation and reception.

Upwelling, Causes and Consequences

Ocean upwelling can be classified as one of four basic types: normal coastal upwelling, equatorial upwelling, open ocean upwelling, and shelf-break coastal upwelling. Normal coastal upwelling occurs when winds produce Ekman transport to the right of wind direction, carrying surface water away from the coast. The usual sequence of events in a coastal upwelling occurrence is as follows: (1) a wind-driven current will move clockwise around an ocean basin (in the northern hemisphere); (2) Ekman transport carries light surface water offshore; (3) the pycnocline (density barrier) between the surface layer and deeper water tilts up towards the shore until it intersects the surface; (4) the upwelling occurs (Narimousa and Maxworthy, 1985). Near the equator, winds drive westward flowing currents. The Coriolis effect pulls the surface water away (to the right or northwest in the northern hemisphere, and to the left or southwest in the southern hemisphere) causing equatorial upwelling. Open ocean upwelling occurs in the form of Langmuir circulation. Steady blowing winds produce diverging currents and create alternating circulation patterns which lead to upwelling and downwelling patterns, primarily in the upper layers. Shelf-break upwelling is a localized coastal upwelling developed because of the significant influence of flow over the depth-change at a shelf's edge.

The importance of upwelling arises from the fact that the subsurface water brought up has extremely different properties than the water that it is replacing. Surface water is normally depleted of its nutrients by the growth of phytoplankton. The colder, denser, upwelled water is usually highly concentrated with nutrient salts such as nitrate, phosphate, and silicate. An increase in productivity, a concentration of species, and shortness of the food chain generally characterize an upwelling zone (Boje and Tomczak, 1978). Maintaining phytoplankton growth, in turn, supports a greater zooplankton concentration. Upwelled regions provide most of the world's important fisheries (Bowden, 1983).

Changing water properties can greatly affect naval operations. Radical changes in temperature profoundly alter the sound velocity profile, thereby affecting sound propagation (Ulrick, 1983). Documentation of upwelling zones is important because the zones may be used for placement of sensors and sonar equipment. The more knowledge gained about the ocean environment, the better it can be utilized for an ASW advantage.

Study Region

The area investigated for upwelling lies between longitude 24°W to 32°W and latitude 62°N to 66°N, near the southwest coast of Iceland. This region contains two submarine canyons with approximate depths of 220 meters. (See Figure 1.) The surrounding coastal shelf area lies at about 150 meters, making the canyons a substantial influence in the bottom topography. The study area contains complex current and circulation patterns which will be further described later.

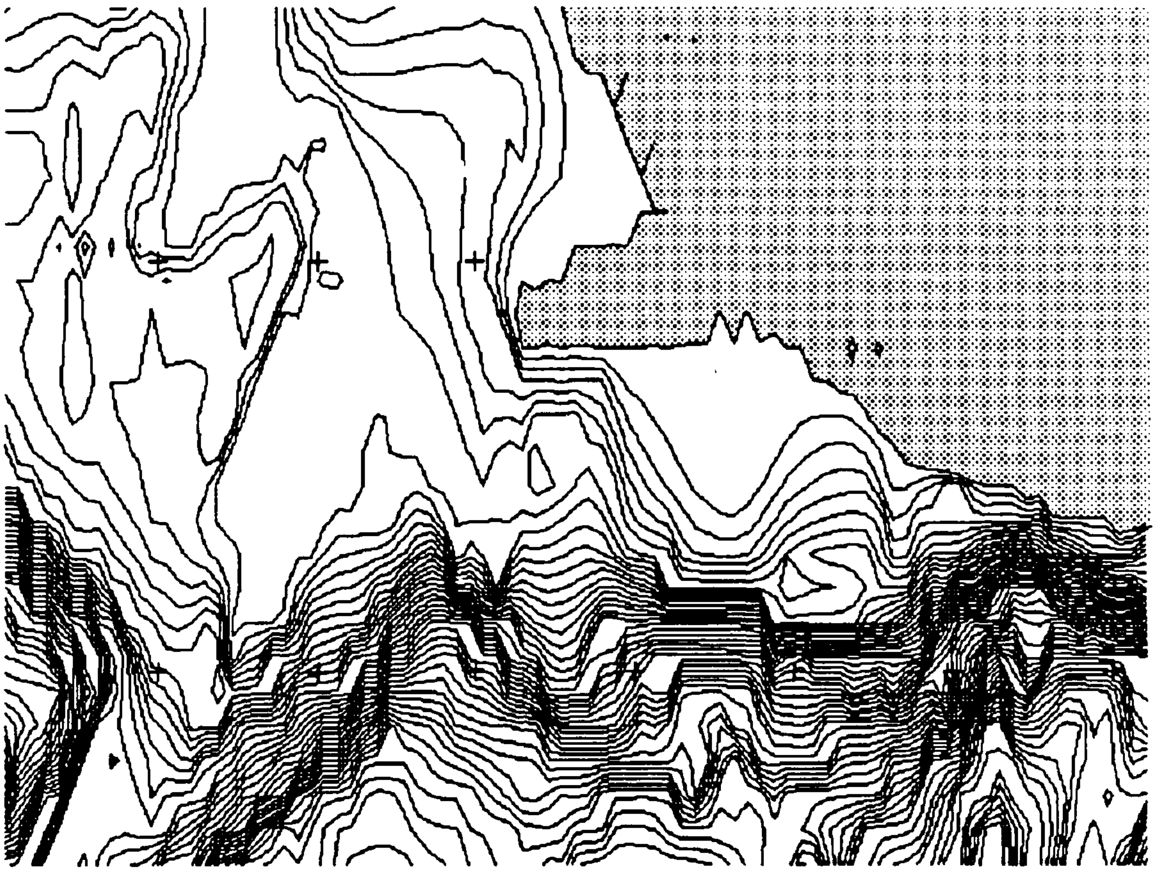

Figure 1. Contour map of the bathymetry around Iceland, with a 30 m contour interval. Two submarine canyons have average depths of 220 m, while the surrounding coastal shelf is at a depth of 150 m; the canyons trend slightly east of north in northwest corner of map.

The Denmark Strait region, somewhat west of the study area, has received attention because of its primary productivity and its importance to the fishery industry. However, the region detailed in this study has been investigated to a minimal extent in the past. This is due primarily to poor sea-state and weather conditions which make it difficult to conduct studies much of the year. Furthermore, cloud-cover over Iceland exists an extensive part of the year, hampering examination of satellite imagery.

The first documented evidence of a possible upwelling are mapped zones of colder water in the study region by Dietrich (1957). The region southwest of Iceland in the Denmark Strait, 65°N, 27.4°W, investigated by Foerster and Thompson (1985), showed an unusual upwelling effect in June 1981. The region under investigation in this study has been known to be one of high productivity in the past, therefore a zone of persistent upwelling would logically support this conclusion (Thordardottir, 1986, Olafsson, 1985, Malmberg, 1985).

THEORY BEHIND EFFECTS OF BOTTOM TOPOGRAPHY

Geostrophic flow arises from the deflective forces caused by the rotation of the earth. Brink's (oral commun., 1989) idealized derivation of the quasi-geostrophic flow over weak bumps (or submarine canyons) considers conservation of potential vorticity as a cause of upwelling. Quasi-geostrophic flow involves a balance between pressure forces and the deflective Coriolis forces caused by the rotation of the earth. It is used to determine currents, because direct measurements of sufficient quantity generally are not possible. When depth increases due to the presence of the submarine canyons, the secondary flow associated with the accompanying change in relative vorticity causes upwelling.

Before applying the quasi-geostrophic flow theory, the principles behind this flow over submarine topography will be examined. In order to achieve geostrophic balance, potential vorticity must be conserved. Potential vorticity, P, is defined as (Bowden, 1983):

$$P = \frac{\delta + f}{H}$$

where H = depth of the water column

$f = 2\ \Omega\ \sin\Phi$ = planetary vorticity

Ω = rotation rate of the earth

and $\delta = \frac{dv}{dx} - \frac{du}{dy}$ = relative vorticity

u,v are the components of velocity in the x,y directions

x and y are positive horizontal axes in the Cartesian coordinate system

f is planetary vorticity (the Coriolis parameter) and for this study it will be assumed constant as it only changes with latitude. In the equation for potential vorticity, if f is held constant and the depth of the water (H) is changed, then δ must change in order to conserve potential vorticity. Therefore, by increasing H, as in flow over a submarine canyon, δ must also be increased. An increase in δ indicates cyclonic flow, conditions favorable for an upwelling. Likewise, a decrease in depth (H) which occurs with flow over a bump or ridge, causes a decrease in δ leading to anticyclonic flow. A change in the current flow after it passes over the topography will cause bottom water to come up. (See Figure 2.)

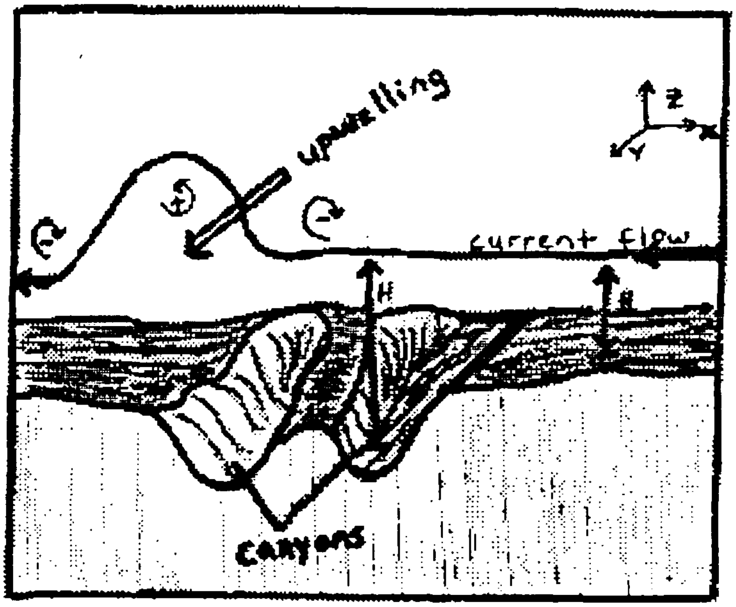

Figure 2. Quasi-geostrophic flow over topography causing upwelling.

EFFECTS OF TOPOGRAPHY

Models of regions of upwelling have rarely considered topographic effects on the circulation. Studies that have examined upwelling in relation to canyons include Shaffer

(1976), Nelson and others (1978), and Freeland and Denman (1982). Freeland and Denman investigated an upwelling event off southern Vancouver Island where a narrow canyon cuts the continental shelf. However, these cases either used narrow canyons in their studies or had poor direct current measurements. Few current measurements have been made over slopes, mainly for two reasons: steep coastal canyons make it difficult to obtain CTD (conductivity, temperature, depth) profiles, and fishing activities make it difficult to maintain moored arrays for very long (Hickey, 1989).

It is well-known that when topographic relief is large geostrophic flow follows depth contours. If scales were made larger the resulting flow may be more geostrophic, modified topographically by following depth contours. Hsueh (1980) used a quasi-geostrophic equation balancing vorticity induced by flow over topography with bottom Ekman pumping to describe the flow in the lower Hudson Shelf Valley which supports this. Also, numerical modeling studies by Hurlburt (1974), Peffly and O'Brien (1976), and Preller and O'Brien (1980) showed that the distribution of upwelling is controlled by topography and favors the equatorial side of canyons. This is primarily due to bottom currents being deflected upwards (Lagerloef, 1984).

Peffley and O'Brien (1976) used a smooth version of the topography to get their results. Lagerloef (1984) took direct current measurements and results from a simplified barotropic potential vorticity model. Both indicated anticyclonic flow around shallow banks tending towards potential vorticity conservation. Relative vorticity then became more anticyclonic along streamlines where flow was toward shallower water.

For a long time oceanographers believed that shoreline features such as shelves and capes had major effects on the dynamics of upwelling. Dynamics of coastal upwelling have been looked at in regions such as those off Oregon, California, West Africa and Peru. It was thought for some time that the strongest upwelling should occur on the downstream side of capes (Narimousa, oral commun., 1989). Recent research, however, suggests that these features have no significant effect, but rather submarine bathymetry plays the critical role. A 1980 investigation of Peru supports this (Preller and O'Brien, 1980). The effect submarine canyons have on circulation patterns appears to play a much larger role than once thought.

Narimousa and Maxworthy (1985) conducted the first experiments on the effects of topography on upwelling. They used a cylindrical tank to simulate an ocean basin and created a ridge system with wind stress and clockwise rotation. They observed the following from their experiment: a zone of maximum upwelling is produced on the downstream edge of the ridge; upstream of the ridge, the pycnocline intersected the surface and migrated as a front away from the shore (Narimousa and Maxworthy, 1985). Application of this experimental result has already yielded successful observations of upwelling patterns in relation to bottom topography. Some events observed to display the above responses occur in the Gulf Stream and the California Current where they cross the Charleston Bump and the Mendocino Escarpment (Narimousa and Maxworthy, 1985).

PREVIOUS WORK

Of the few studies conducted off the west coast of Iceland, most were done in the past three decades by Icelanders in order to investigate the primary productivity of the region. They mainly concentrated on collection of hydrographic variables and observations of spring bloomings of phytoplankton. My research into a number of their reports has provided this study with substantial information supporting upwelling in the region caused by the topography. Evidence has been gained from current analyses, productivity reports, and hydrographic conditions. While I have synthesized data collected from studies in past years, those investigations were primarily productivity studies and did not attempt to postulate reasons for abnormal hydrographic conditions. Besides those mentioned previously, other studies examined include Malmberg (1980, 1985), Stefansson (1968), and Thordardottir and Stefansson (1977).

The study conducted by Foerster and Thompson in 1981, in an attempt to discover causes for plankton and whaling ground dynamics, was the first to attribute the unstable water in the region southwest of Iceland to an upwelling occurrence. This research project examined the upwelling region, conclusions of the Foerster and Thompson study, and possible causes of the upwelling.

The initial Foerster and Thompson study utilized the advanced very high resolution radiometer (AVHRR) weather satellites to interpret cloud-free images of sea surface temperatures. Images from the NOAA-6 and NOAA-7 satellites from 1979, 1980, and 1981 showed temperature patterns indicating upwelling. An oceanographic expedition conducted 1 - 17 June 1981 produced calculations revealing a mean water mass transport to the northwest. Winds during the study predominantly blew from the north to northeast averaging 9.0 m/s (Foerster and Thompson, 1985). The NOAA-6 satellite data from April to June 1981 showed a consistent wind flow from the north to northeast. Foerster and Thompson also analyzed expendable bathythermograph (XBT) data. Salinity was nearly constant with exceptions at both the approximate site for the upwelling and over the mouth of the submarine canyon where there were slight increases. Temperature patterns appeared to be uniform indicating no definite thermocline. The bending upward of density layers near the Iceland shelf, 63-64° N by 24-25° W, further suggested upwelling (Foerster and Thompson, 1985).

To satisfy a wind-induced upwelling, conditions would require a steady flowing wind of sufficient duration. Foerster and Thompson concluded: (1) a north-northeast wind created an upwelling slightly to the west of the shelf break (200 m); (2) zooplankton appeared to be concentrated east of the upwelling; (3) the current pattern consisted of northward flow on the east side of the upwelling, and a southward moving current to the west of it. Furthermore, they considered other ocean dynamics including convergence created by a geostrophic flow, but discounted geostrophic flow due to the lack of significant dynamic topography in the study area.

DATA SUPPORTING UPWELLING

To demonstrate that this unusual upwelling occurrence is in fact due to flow over topography, I examined the following:

- wind analysis (wind rose plots, documented observations)
- currents
- productivity studies
- sea surface temperature data (surface maps, vertical profiles)
- temperature doming (satellite images, past history)

The data that will be presented indicate that a persistent upwelling does exist. Table I summarizes the evidence for upwelling.

Table 1. Evidence Supporting Upwelling Southwest of Iceland

Time	Location	Evidence	Source
1-6 Jun 1973	64.25°N 26.00°W	SST Map	Interpretation of Malmberg, 1973
21 May - 8 Jun 74	63.50°N 26.00°W	SST Map	Interpretation of Malmberg, 1974
25 May - 15 Jun 76	63.50°N 26.50°W	SST Map	Interpretation of Malmberg, 1976
21 May - 12 Jun 77	63.75°N 25.80°W	SST Map	Interpretation of Malmberg, 1977
23 May - 14 Jun 78	63.40°N 25.50°W	SST Map	Interpretation of Malmberg, 1978
27 May - 15 Jun 79	64.50°N 26.00°W	SST Map	Interpretation of Malmberg, 1980b
20 May - 10 Jun 81	63.50°N 26.00°W	SST Map	Interpretation of Malmberg, 1983
25 May - 14 Jun 82	64.00°N 26.25°W	SST Map	Interpretation of Malmberg, 1983
May 1975	64.00°N 24-28°W	Temperature Profile	Interpretation of Malmberg, 1975
May 1976	64.00°N 24-28°W	Temperature Profile	Interpretation of Malmberg, 1976
May 1977	64.00°N 24-28°W	Temperature Profile	Interpretation of Malmberg, 1977
May 1978	64.00°N 24-28°W	Temperature Profile	Interpretation of Malmberg, 1978
29 May - 21 Jun 81	63-66°N 21-28°W	Variable Avg Winds	Schollaert 1988a
20 Aug - 28 Aug 81	63-66°N 21-28°W	Variable Avg Winds	Schollaert 1988a
Dec-Feb 1950-1975	60-65°N 20-30°W	Mean Wind stress	Thompson and Hazen 1983

Table I. (Continued).

Time	Location	Evidence	Source
Mar-May 1950-1975	60-65°N 20-30°W	Mean Wind stress	Thompson and Hazen 1983
Jun-Aug 1950-1975	60-65°N 20-30°W	Mean Wind stress	Thompson and Hazen 1983
Sep-Nov 1950-1975	60-65°N 20-30°W	Mean Wind stress	Thompson and Hazen 1983
Monthly 1982	62-65°N 23-27°W	Sfc Currents & wind roses	Pilot Charts of the North Atlantic
Apr-May 1976-81	63-66°N 22-28°W	Surface Currents	Glade, and others, 1963
September 1963	63-66°N 23-28°W	Surface Currents	Olafsson, 1985
Jan-Mar 1979	SW coast Iceland	CZCS images, phytoplankton	Feldman, 1979
Apr-Jun 1979	SW coast Iceland	CZCS images, phytoplankton	Feldman, 1979
Jul-Sep 1979	SW coast Iceland	CZCS images, phytoplankton	Feldman, 1979
Monthly 1979	SW coast Iceland	CZCS images, phytoplankton	Feldman, 1979
August 1981	63.00°N 25.00°W	SST images	This study: AVHRR GAC Data
April 1982	64.25°N 26.00°W	SST images	This study: AVHRR GAC Data
June 1982	64.50°N 25.50°W	SST images	This study: AVHRR GAC Data
July 1982	64.00°N 27.00°W	SST images	This study: AVHRR GAC Data
May 1983	64.50°N 26.00°W	SST images	This study: AVHRR GAC Data
June 1983	64.00°N 27.00°W	SST images	This study: AVHRR GAC Data

Table I. (Continued)

Time	Location	Evidence	Source
August 1984	63.00°N 25.00°W	SST images	This study: AVHRR GAC Data
May Average	64.00°N 23.50°W	plotted SST Maps	This study: MBT data
June Average	63.50°N 23.50°W	plotted SST Maps	This study: MBT data
July Average	63.80°N 24.30°W	plotted SST Maps	This study: MBT data
February Average	64.20°N 24.00°W	plotted SST Maps	This study: XBT data
March Average	64.50°N 23.20°W	plotted SST Maps	This study: XBT data
April Average	64.50°N 24.00°W	plotted SST Maps	This study: XBT data
May Average	64.70°N 24.60°W	plotted SST Maps	This study: XBT data
June Average	64.80°N 24.80°W	plotted SST Maps	This study: XBT data
July Average	64.50°N 25.50°W	plotted SST Maps	This study: XBT data
August Average	64.00°N 24.50°W	plotted SST Maps	This study: XBT data
September Average	64.20°N 24.00°W	plotted SST Maps	This study: XBT data
October Average	64.40°N 25.80°W	plotted SST Maps	This study: XBT data
December Average	64.40°N 24.00°W	plotted SST Maps	This study: XBT data

Notes:

AVHRR, Advanced Very High Resolution Radiometer
CZCS, Coastal Zone Color Scanner
GAC, Global Area Coverage
MBT, mechanical bathythermograph
SST, sea surface temperature
XBT, expendable bathythermograph

Wind Analysis

Foerster and Thompson (1985) have hypothesized that wind movement induces the upwelling, which thereby helps to create the observed feeding ground. They state that winds were from the north and northeast directions, responding to the Icelandic low pressure center, and consequently resulted in a water mass transport to the northwest. Their generalized model for the winds does not appear to be valid.

First, seasonal mean wind stress maps, averaged for twenty-five years and shown in Figure 3, indicate winds from the southeast (Thompson and Hazen, 1983). Wind stress contributes to circulation of coastal waters and the advection of phytoplankton. Thompson and Hazen calculated geostrophic winds from monthly air pressure charts and then substituted them into a quadratic stress law to give wind stress. Secondly, in order for the upwelling to have been wind-driven, winds would have to be constant. Wind driven causes for upwelling would only be possible if wind were constant over some large given time period. Schollaert (1988a, 1988b) analyzed the time period 29 May - 21 June 1981 and 20-28 August 1981, the same period studied in the Foerster and Thompson analysis. After an evaluation of synoptic surface weather charts, a geostrophic wind was computed and no predominant wind pattern was found in the 64°N, 26°W study region (Schollaert, 1988a, 1988b).

Further investigation of wind patterns by this study continues to show fluctuating prevailing winds. Wind rose plots for each month in 1982, showing distribution of wind directions, support variable wind directions (Defense Mapping Agency, 1982). None provide any indication of a dominant wind pattern in the southwest Iceland region. Other indications of variable winds include three distinct wind patterns identified in the region during a productivity study conducted by Thordardottir (1986). She also noted that these winds were presumably not strong enough to cause upwelling.

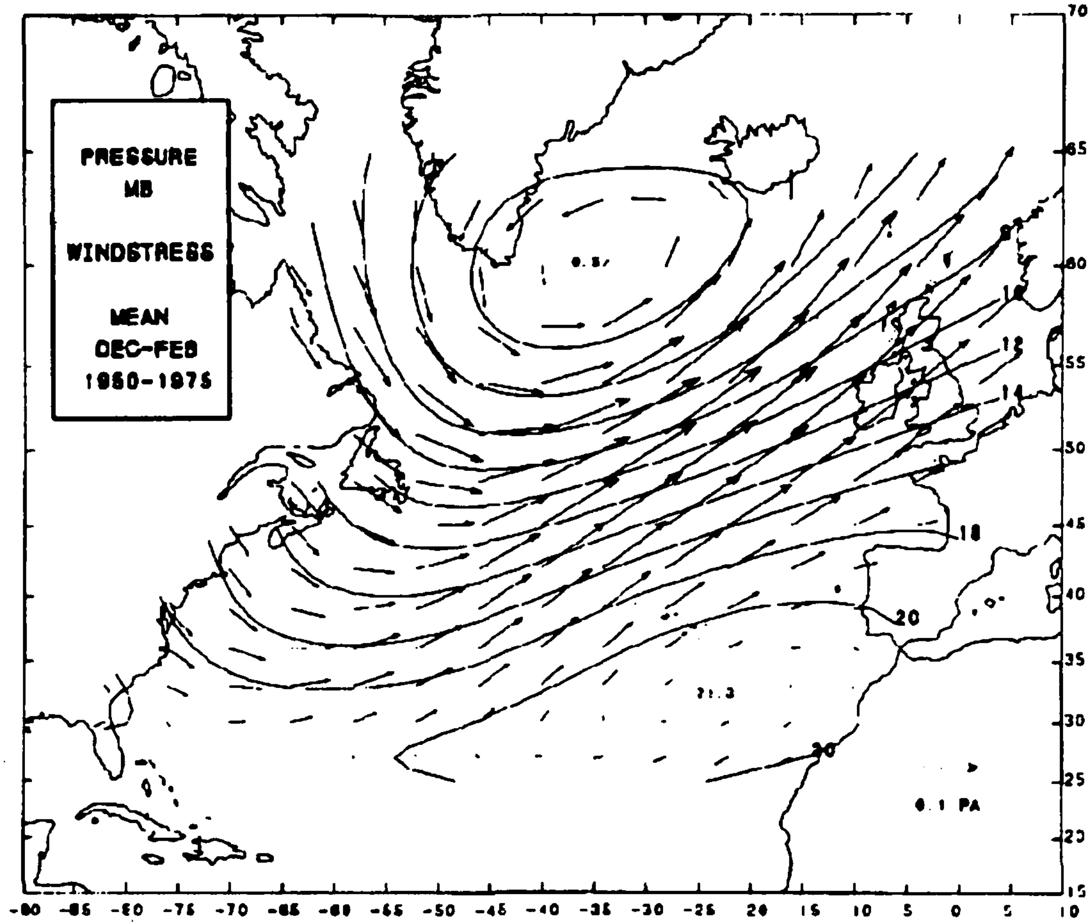

Figure 3. Computed seasonal wind stress maps from calculated geostrophic winds (Thompson and Hazen, 1983)

a. Mean wind stress for Dec-Feb, 1950-1975

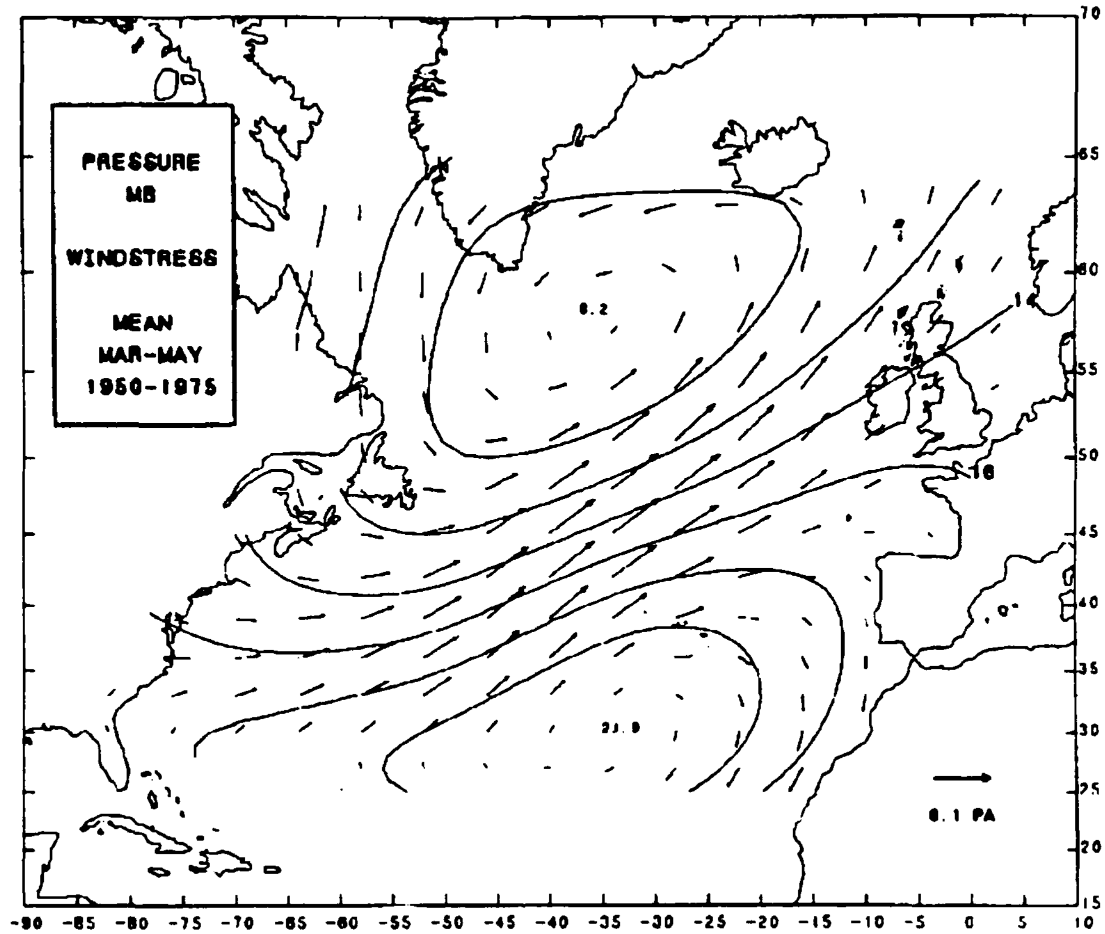

Figure 3 b. Mean wind stress for Mar-May, 1950-1975

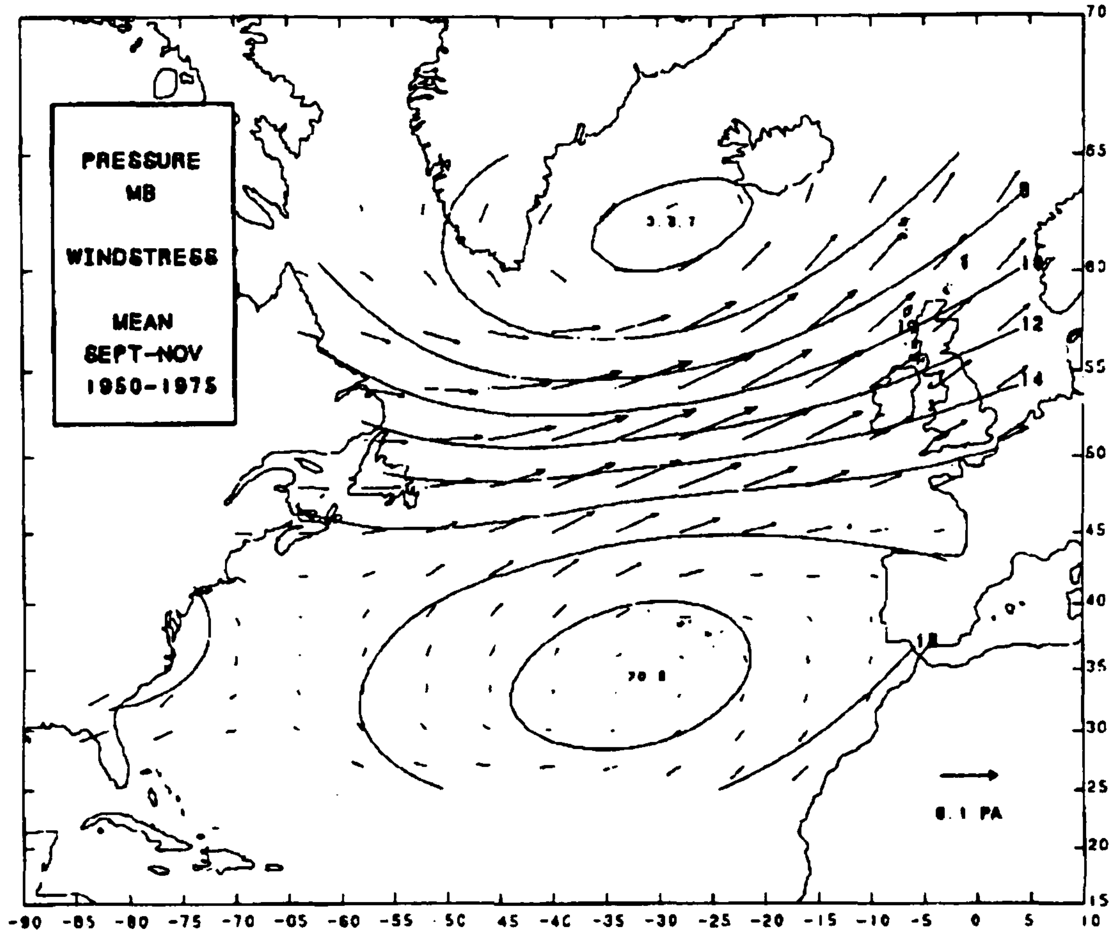

Figure 3 c. Mean wind stress for Sep-Nov, 1950-1975

Current System

Examination of the currents around Iceland reveals a fairly complex system due, in part, to the fact that the island is located where Atlantic and Arctic waters join together. The Irminger Current flows southeast to northwest around the west coast of Iceland, thus in a northerly direction over the submarine canyons. The U.S. Naval Oceanographic Office's Atlas of the North Atlantic (1965) charts seasonal prevailing surface currents. Current flow is consistently from the southeast to northwest direction. However, strength of the current appears to vary on a seasonal basis with stronger currents in March to August (U.S. Naval Oceanographic Office, 1965).

The effects of submarine bathymetry on local flow fields enhance upwelling on the downstream side of canyons (Narimousa, oral commun., 1989). In order for the upwelling occurrences off the Iceland coast to have been caused by the local topography, a mean current moving northward over the submarine canyons is necessary.

The earliest current measurements were conducted by Hermann and Thomsen with drift bottle experiments; they found a mean surface current flowing clockwise around the island (Hermann and Thomsen, 1946). Malmberg's investigations agree with this flow pattern and found the current to have a speed of three to five miles a day in the area south and west of Iceland (Malmberg, 1968). Figure 4 indicates surface currents in the northern Irminger Sea based on dynamical calculations (Glade and other, 1963). Olafsson, while attempting to relate recruitment of Icelandic cod and haddock stocks to physical variables, noted a geostrophic current west of Reykjanes which moved northward past the Faxafloi region in the vicinity of 64°N, 26.5°W (Olafsson, 1985). This is displayed in Figure 5.

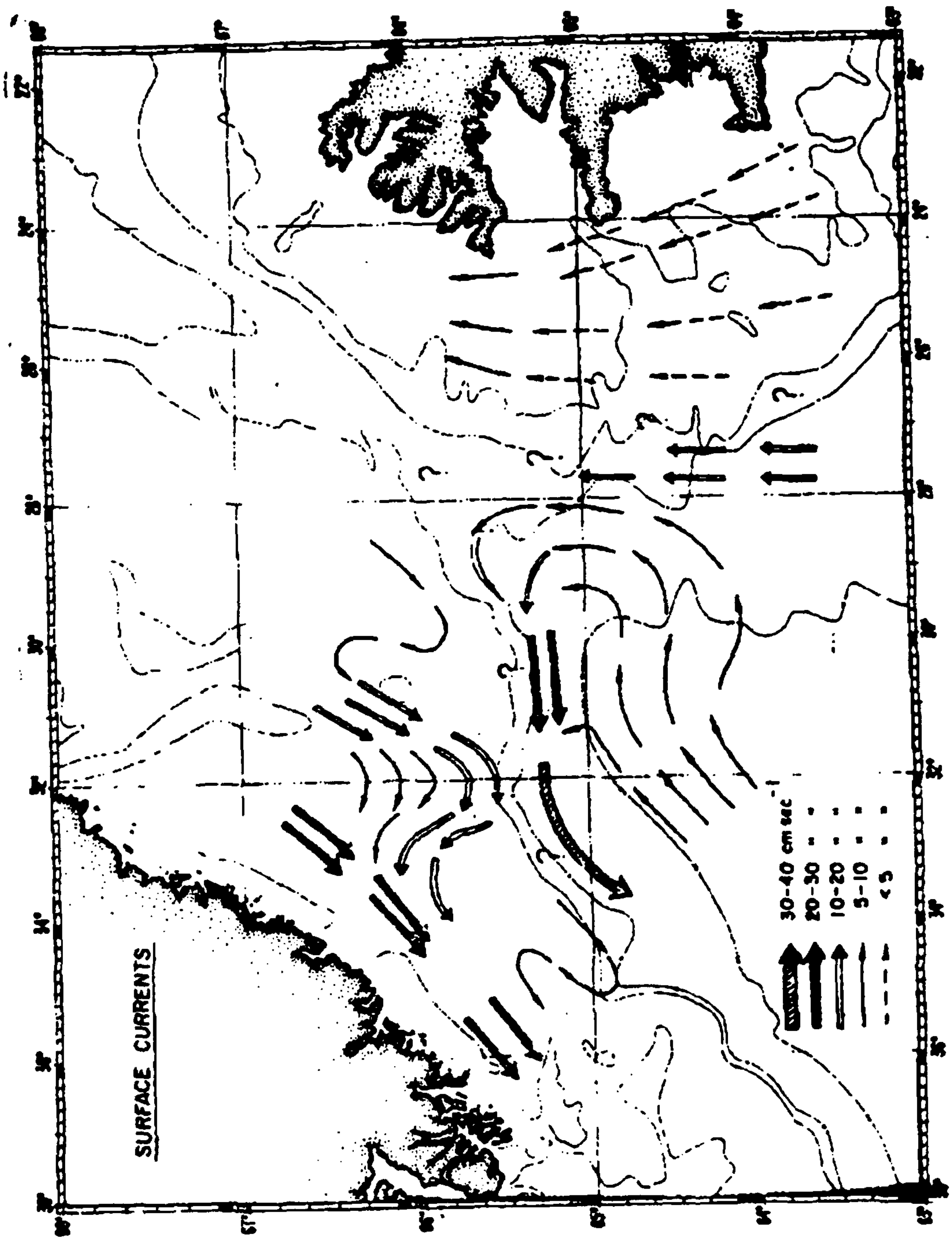

Figure 4. Surface currents based on dynamic topography (Glade and others, 1963).

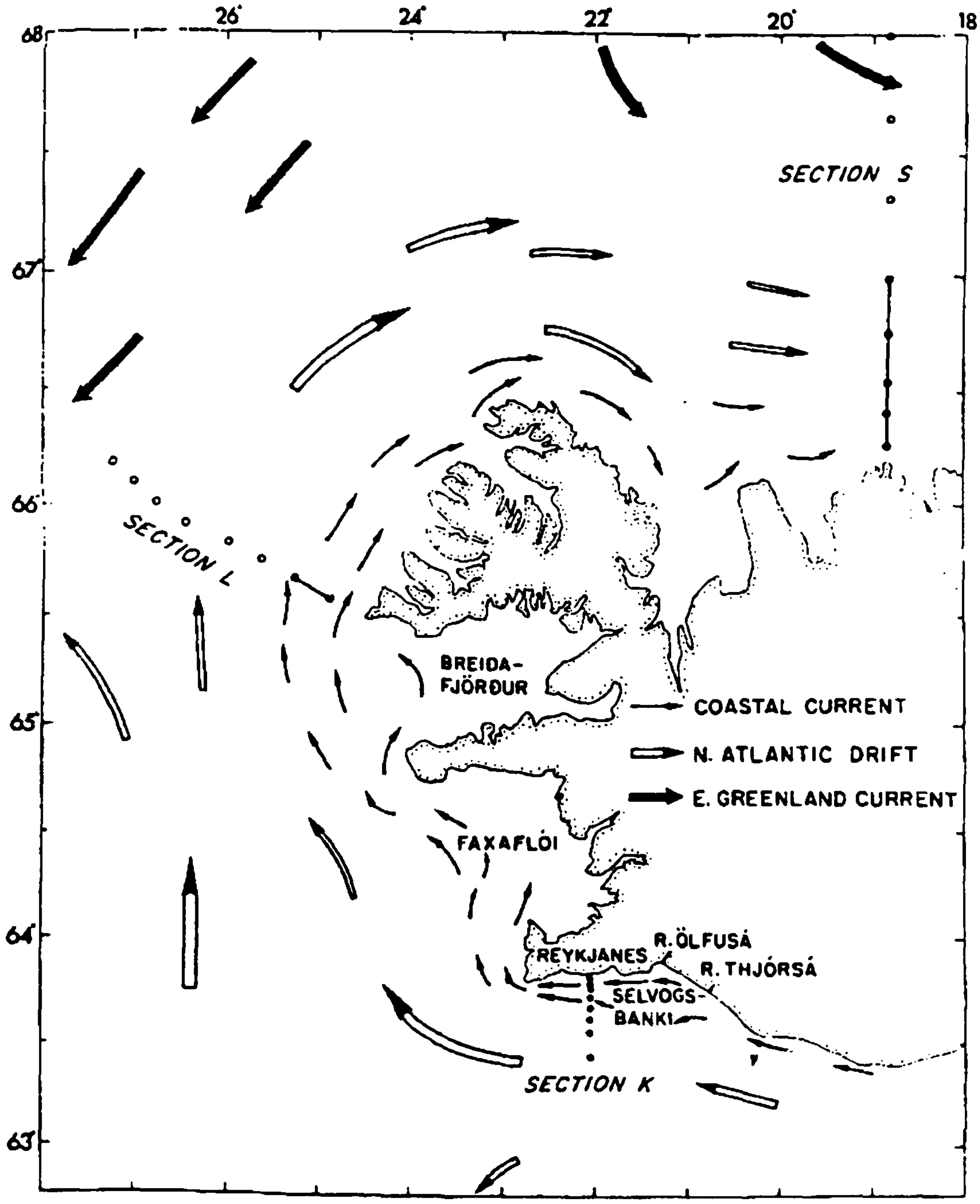

Figure 5. Surface current patterns from current meter measurements (Olafsson, 1985).

Interpretation of Productivity Observations

The effect of the physical environment in the southwest Iceland region on the primary productivity has been recognized, and also seems to have been significantly influenced by upwelling in the submarine canyon. The main spawning grounds for Icelandic haddock and cod stocks are found south and southwest of Iceland. In general, blooming starts in coastal waters and is delayed with increasing distance from the land. However, studies for a number of individual years show results which indicate varying onsets of blooming as well as the changes in the length of the blooms in regions farther off the coast (Thordardottir, 1986). Some of these results coincide with the region of upwelling under investigation in this study. Thordardottir and Stefansson (1977) investigated primary productivity and noticed that in the region west to south of Reykjanes (64°N, 25°W), there was a continued renewal of nutrients to the photic zone. Their report stated that, "we can offer no well-established explanation of these regional differences in primary production. However, we propose as a possible hypothesis that water entering the study area from the region south of Reykjanes may be relatively nutrient rich, possibly due to turbulent mixing as it flows across the Reykjanes Ridge" (Thordardottir and Stefansson, 1977). Stefansson (1968) also discovered nitrate-phosphate relationships to be much higher in the study region than at a number of nearshore stations, typically with higher levels (Stefansson, 1968).

Productivity relates directly to water conditions. For example, the intrusion of Atlantic water in regions farther south (around 63.5°N, 25°W) in the spring provides for the continued renewal of nutrients to the southern spawning areas. The high productivity in areas a bit farther north and off the coast (such as the region of interest in this study) must also be experiencing a renewal of nutrients. Thordardottir (1986), Malmberg (1985), and Stefansson (1968) have all noted lower temperatures and high productivity off the west coast of Iceland with little explanation to their cause. I believe their research strongly points to upwelling as the generating source.

Sea Surface Temperature Data

Mean charts of sea surface temperatures and salinities are useful tools in oceanographic research. Sea-surface temperature maps provide a good indication of an upwelling occurrence. When the isotherms, lines of constant temperature, drop in the vicinity of the study region, an intrusion of colder water has occurred. Monthly averages are the best way to pinpoint a persistent upwelling since the effects of one upwelling event typically last much longer than a few days.

Hydrographic surveys were conducted around the coast of Iceland yearly from 1973 until 1983 for the May-June time period. Temperature and salinity observations were taken by Icelanders for the Meteorological Institute and published yearly in Annales Biologiques. Sea surface temperature (SST) maps plotted for each year of this ten year period indicate a significant dip in the temperature isotherm off the southwest coast of Iceland. (See Table I.) Representative SST maps from 1-6 June 1973, 5 May - 10 June 1981, and 25 May - 14 June 1982 are shown in Figure 6. Table I indicates a number of the time periods and the locations of upwelling events interpreted to have occurred. The repeated lowering of the temperature in the vicinity of the study region points to a persistent upwelling feature.

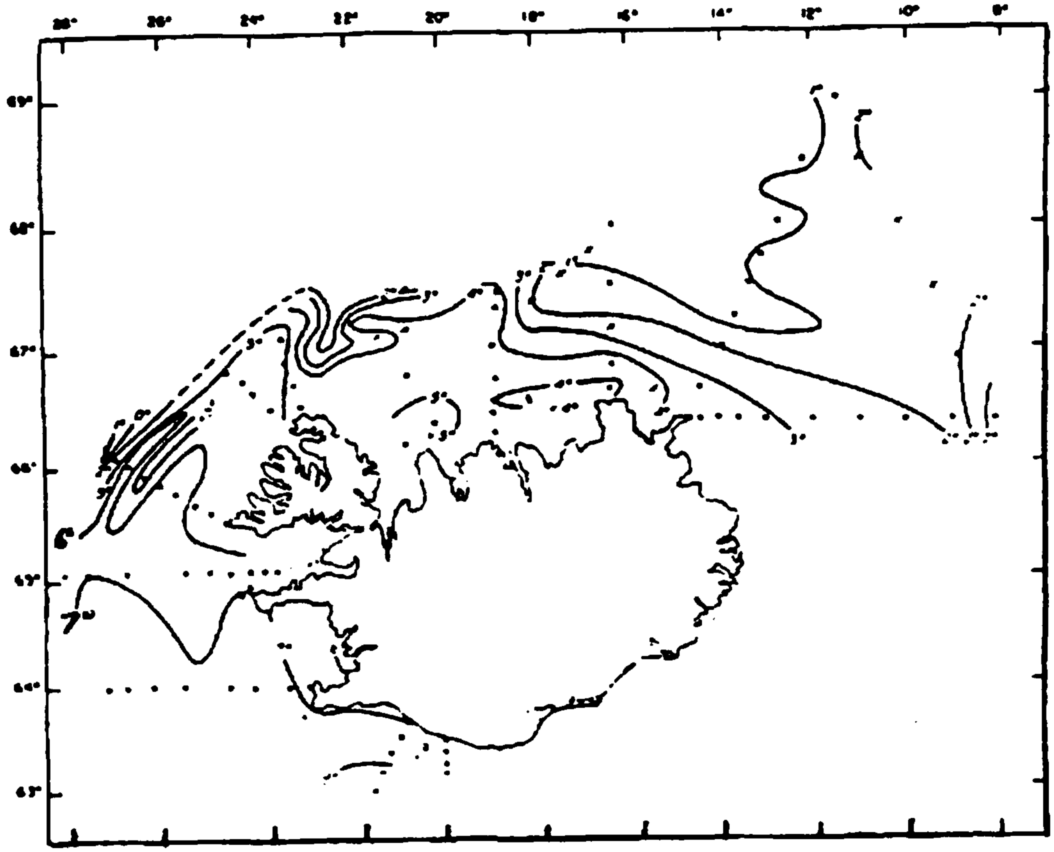

Figure 6 a. Sea surface temperatures, 1-16 June 1973 (Malmberg, 1973). The 7°C isotherm dips down to nearly 64°N, indicating the colder waters present in the study region.

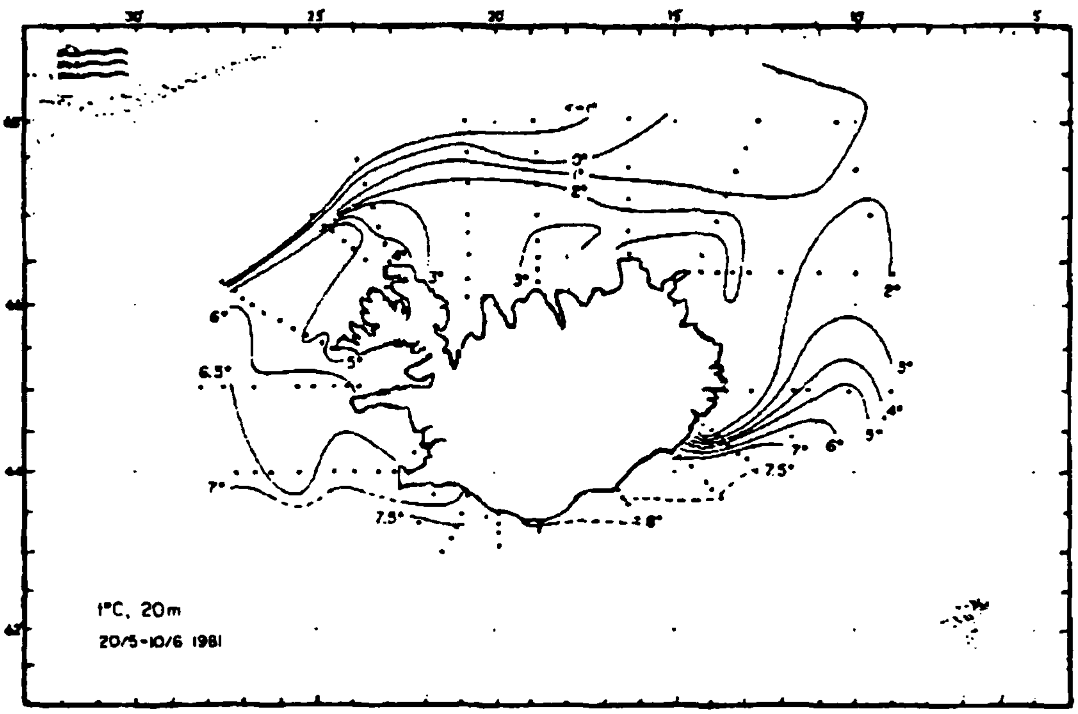

Figure 6 b. Sea surface temperatures, 20 May-10 June 1981 (Malmberg, 1983); The 6.5°C isotherm dips down well into the study region.

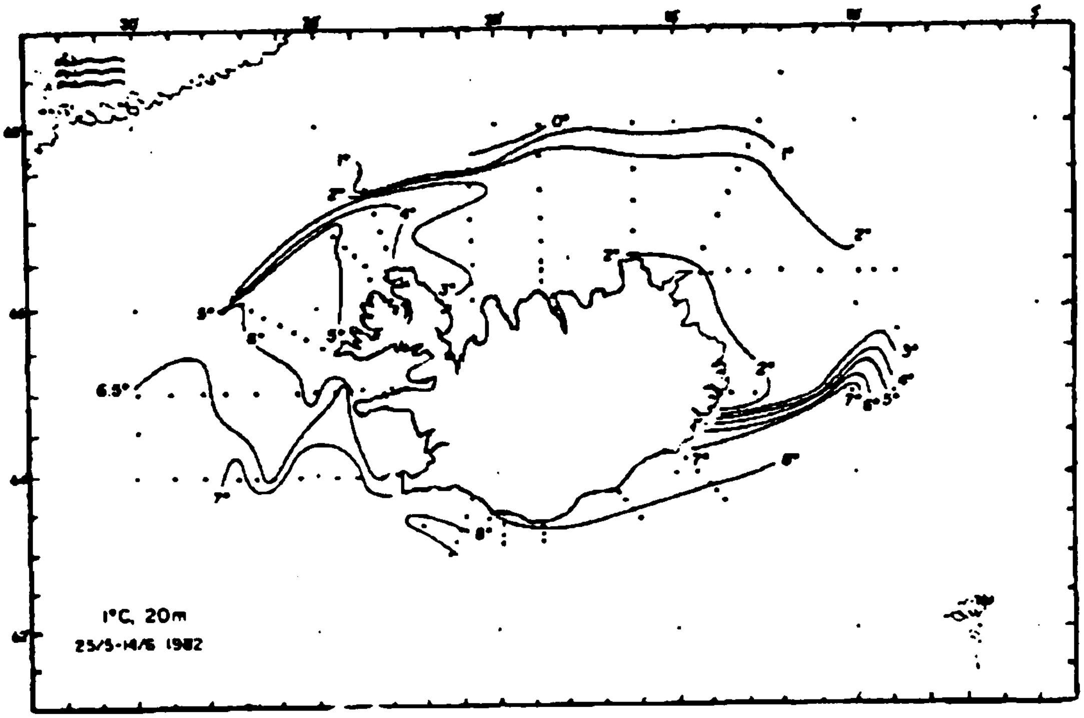

Figure 6 c. Sea surface temperatures, 25 May-14 June 1982 (Malmberg, 1983); The 6.5° and 7°C isotherms also dip down in the same pattern indicating a probable upwelling event.

Vertical temperature profiles provide another good indication of an upwelling occurrence. The pattern of isotherms in the vertical, in relation to the bathymetry, pinpoints the upwelling in a number of documented figures. Upon examination of the profiles, those which have isotherms curving up to form a domal pattern in relation to the bathymetry are indicative of an upwelling. The hydrographic data previously mentioned were also plotted on profile maps. Figure 7 includes profiles indicating the temperature doming that does exist in the study region off the Rekyjanes

Peninsula. This finding was consistent over the ten year period.

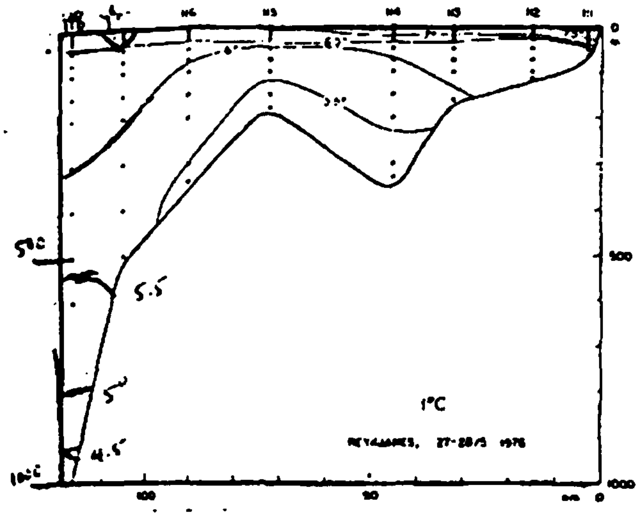

Figure 7 a. Temperature profile maps off Reykjanes (64°N, 26°W), May 1976 (Malmberg 1976).

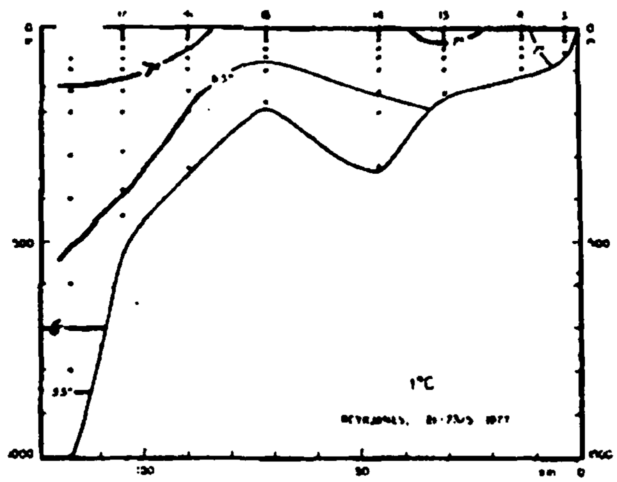

Figure 7 b. Temperature profile maps off Reykjanes (64°N, 26°W), May 1977 (Malmberg 1977).

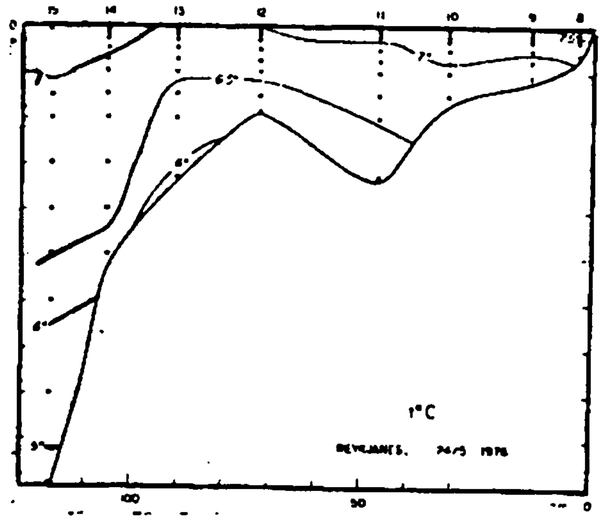

Figure 7 c. Temperature profile maps off Reykjanes (64°N, 26°W), May 1978 (Malmberg 1978).

Since very few SST maps of the study region have been developed, raw hydrographic data were acquired to provide more evidence for the verification of an upwelling event. Raw expendable bathythermograph (XBT) and mechanical bathythermograph (MBT) data were obtained from the National Ocean Survey. Monthly SST maps were plotted and then examined for possible upwelling events. (See Appendix A.) The data clearly point to a persistent upwelling as shown by the significant drops in the isotherms. A few of the months are pictured in Figures 8 - 12. Table I lists all the SST maps produced by this research project which indicate upwelling events in the vicinity of the study area (64°N, 26°W is the probable center for the upwelling).

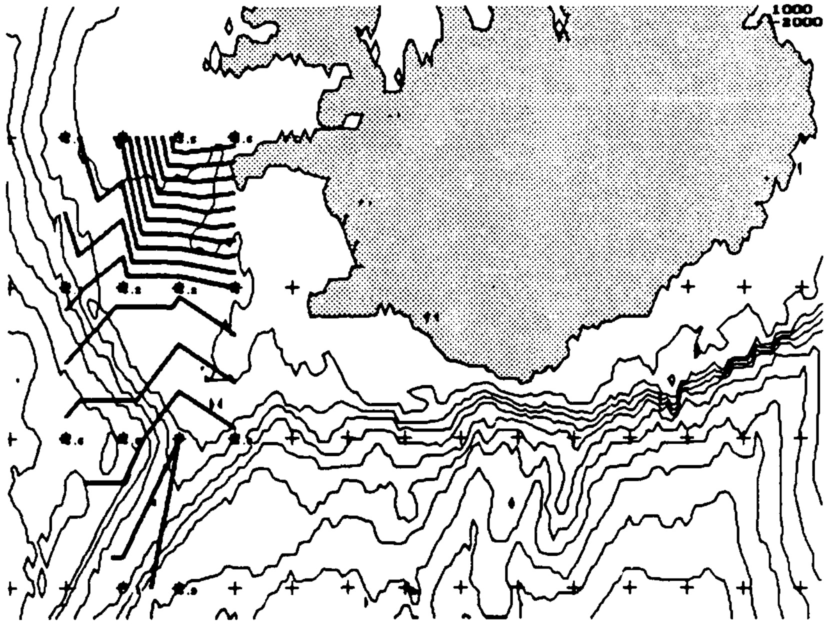

Figure 8. Sea surface temperature map plotted from MBT data, averaged for the month of March. The thin lines show the bathymetry around Iceland with a contour interval of 30 m. The thick lines are isotherms with 0.25°C contours and show moving colder water into the study region.

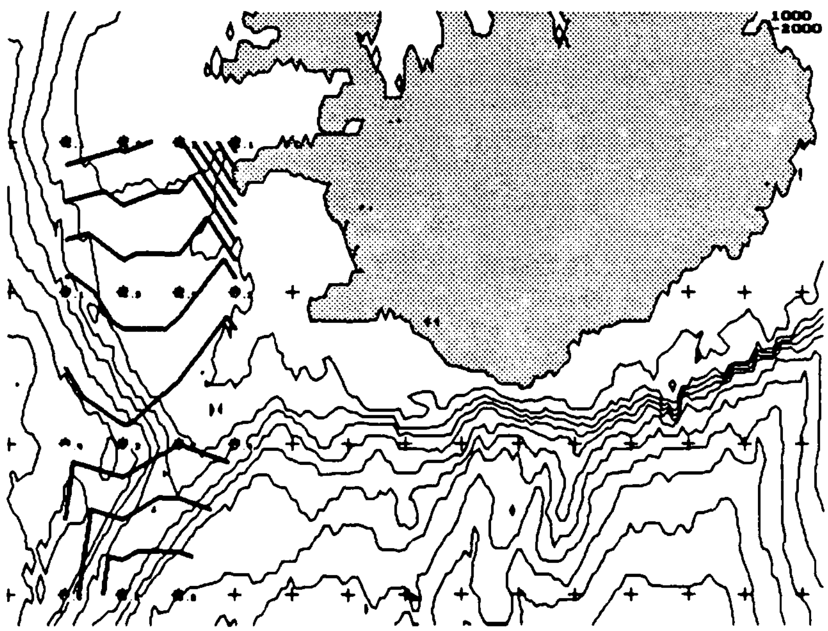

Figure 9. Sea surface temperature map plotted from MBT data, averaged for the month of May. Isotherm contours at 0.5°C.

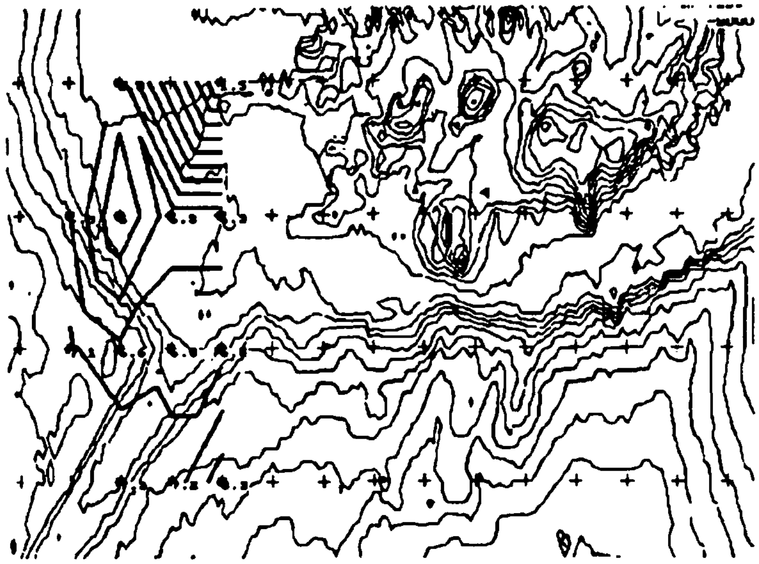

Figure 10. Sea surface temperature map plotted from XBT data, averaged for the month of June. Isotherm contours at 0.5°C.

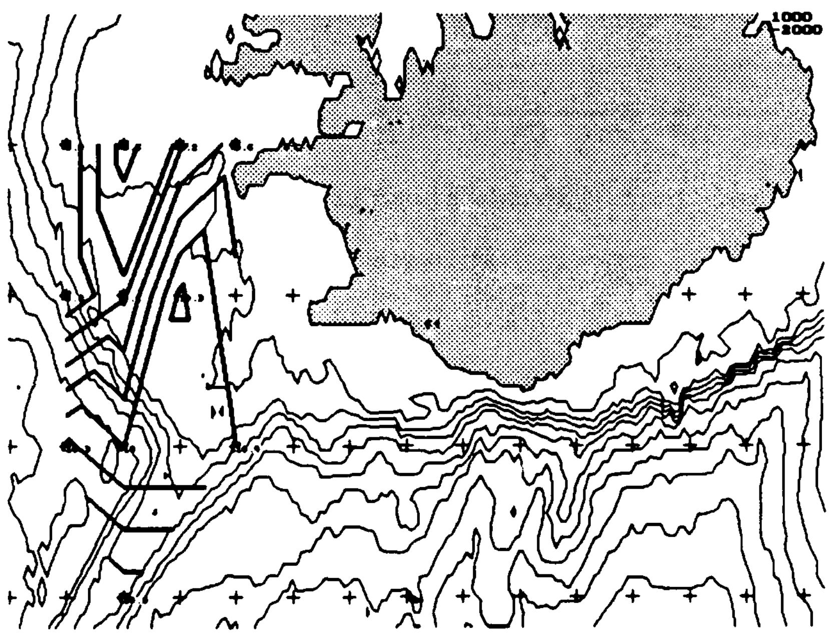

Figure 11. Sea surface temperature map plotted from XBT data, averaged for the month of September. Isotherm contours at 0.25°C.

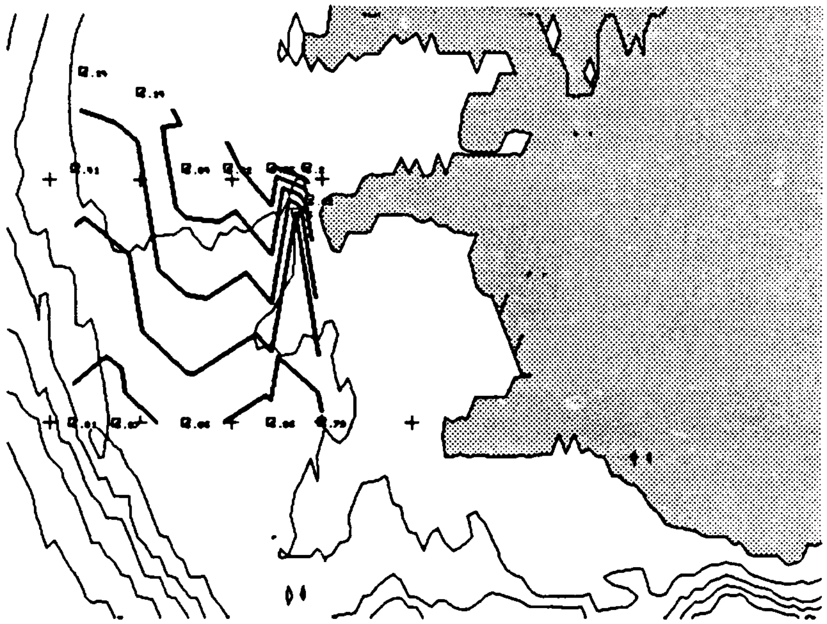

Figure 12. Sea surface temperature map plotted from XBT data, averaged for the month of December. Isotherm contours at 0.25°C.

Examination of Satellite Imagery

In the last decade satellites have played an immensely important role in the identification of oceanographic phenomena. Investigation of imagery has allowed insight into a number of areas of the globe minimally traversed by research vessels in the past. The areas off Iceland have had few surveys conducted in the surrounding waters. The use of satellite imagery and remote sensing techniques to aid in the documentation of the upwelling occurrences off the Iceland coast have played a sizable role in this research effort.

In their initial investigation, Foerster and Thompson (1985) used a program called SEATEMP to interpret digital satellite data. The Nimbus-7 Coastal Zone Color Scanner (CZCS) was launched by NASA in 1978 to make ocean color measurements from space. Data collected by the CZCS were used to verify phytoplankton distribution and high productivity in Icelandic waters (Clark and Maynard, 1986). I also examined CZCS images for the year 1979. Various seasonal as well as monthly composites show a high phytoplankton distribution off the southwest coast of Iceland. (See Table I.)

This study has also utilized NOAA Advanced Very High Resolution Radiometer (AVHRR) data, from the NOAA-7 polar orbiting satellite, to investigate the unstable waters off Iceland and to verify a temperature "doming" pointing to a persistent bottom-generated feature. (See Appendix B.) The satellite measures emitted thermal radiation. The various intensities can then be combined to produce sea surface temperatures. The development of sea surface temperature maps is very useful in the identification of upwelling zones.

The significantly colder water present in the vicinity of the study area is shown in Figures 13 and 14 and indicates the presence of an upwelling event. Cold upwelling water appears dark in the images, while warmer surface waters are lighter. A total of eight scenes were analyzed for various months between August 1981 and August

1984. Seven of these pointed to a persistent upwelling occurrence. Those scenes which clearly displayed colder surface waters in the study area relative to the surrounding waters are noted in Table I. The only scene which did not display cold upwelled water was August 1982.

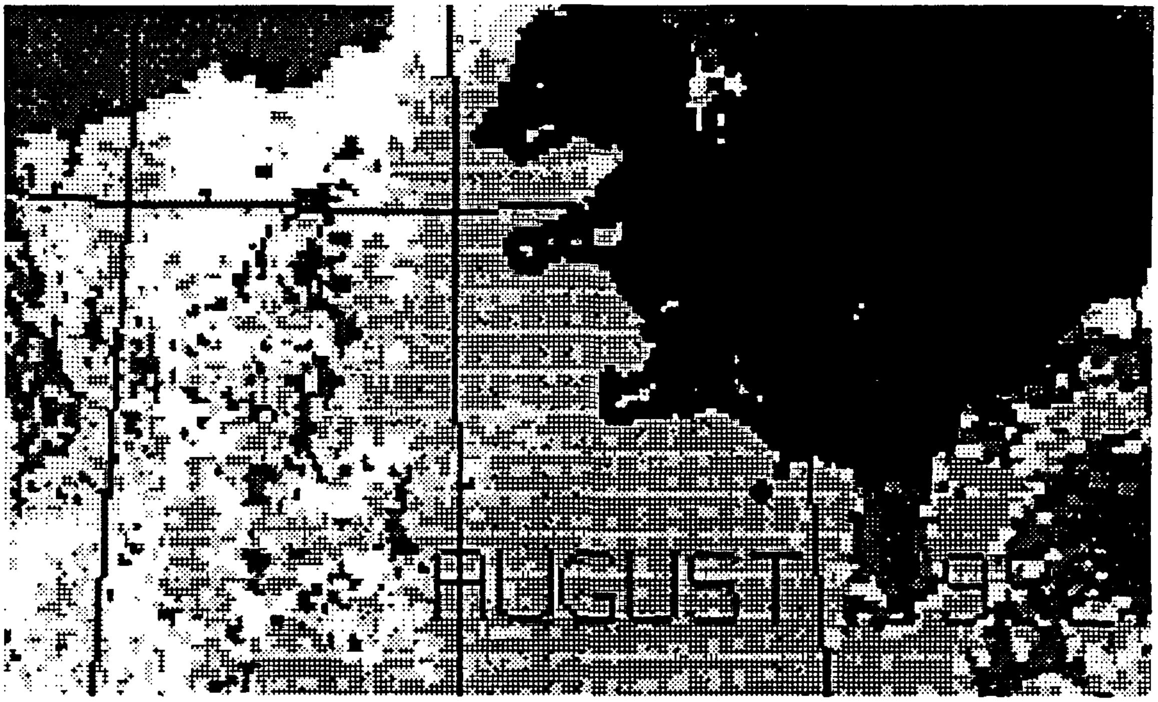

Figure 13. AVHRR satellite image of sea surface temperatures, August 1982

Figure 14. AVHRR satellite image of sea surface temperatures, June 1983

MARINE BATHYMETRY AND ASW

The Iceland region is not only important to study for scientific reasons, but it is also of great strategic importance to the U.S. Navy. Of vital concern are the submarine operations conducted in the North Sea and the Denmark Strait. The importance of submarine bathymetry in undersea warfare is particularly noteworthy in a number of areas including sound transmission, submarine navigation, submarine concealment, and sonar acquisition. An understanding of the importance of bathymetry and the use of bathymetric charts and information is necessary for efficient ASW operations. Providing environmental support to the fleet, accurate acoustic information, and ocean environment data are absolutely essential.

One application of bathymetry to ASW operations is the use of convergence zones. It has been observed that convergence zone (CZ) detection is unlikely in warm or moderately warm water in depths of less than 1200 fathoms, but that they can exist in depths as shallow as 300 fathoms under certain conditions (Russum, 1988). The presence of underwater bathymetric features such as a seamount, ridge, or shoal area may effectively block the CZ path. The existence of CZ sound paths plays a major importance in search and detection for ASW tactics (Urick, 1983). Bathymetric interference is another consideration since ocean bottom features can provide concealment for submarines by redirecting and blocking sound waves.

Other oceanographic features such as water masses, transition zones, cold and warm water eddies, internal waves, and currents produce changes in the thermal structure of the water (Russum, 1988). The water mass of a specific region can be modified to take on different thermohaline characteristics. Upwelling will modify a water mass introducing new temperature and salinity properties. Transitional zones are important to examine because they are indicative of crucial variations in oceanographic conditions and also of corresponding changes in sonar conditions. Eddies, rotating gyres of warm or cold water up to 200 nautical miles in diameter, can also form in upwelling regions.

The major surface currents and the layered structure of the ocean play a considerable role in the way we conduct acoustic operations. In underwater acoustics water properties determine the transmission of sound. In the upper layers of the ocean, temperature and salinity are the dominant factors affecting sound speed. Oceanographic upwellings provide significant changes in sea-surface temperatures, salinities, and the mixed-layer depth. Analysis of charts will show little day-to-day variation as a result of an upwelling; however, seasonal changes in the ocean thermal structure are affected and can be noted by examination of satellite imagery.

As mentioned previously, upwelling can have profound biological effects which are important for the Navy's interests, as well as for the commercial fishing industry. If a water medium is heavily concentrated with fish, plankton, and bubbles, scattering and reverberation losses will be a problem. With these propagation losses, acoustic energy is reflected away from or back to the receiver by the discontinuities present. Marine organisms containing swim bladders that resonate at 3.5 KHZ are suspected as volume scatterers. (Urick, 1984)

CONCLUSION

Investigation into an unusual upwelling event off the southwest Iceland coast first attributed to a shelf-break upwelling now appears instead to be caused by flow over local topography. A thorough documentation of the upwelling points to a persistent feature. A shelf-break occurrence would require steady winds or an inconsistent upwelling event due to changing wind patterns. Quasi-geostrophic flow over two significant submarine canyons instead was postulated as the cause for the upwelling. Potential vorticity must be conserved when the depth of the water column changes. Recent studies into the effects of flow over topography indicate upwelling events result downstream in the presence of a submarine canyon. Analyses of wind patterns, current observations, hydrographic data, and satellite imagery lead to the conclusion that a persistent upwelling event exists in the area 64°N, 26°W, and that flow over local bottom topography is the most likely cause.

ACKNOWLEDGMENTS

Stephanie Schollaert began the initial research on this upwelling as part of an independent study she conducted her first class year (Schollaert, 1988a, 1988b) under Visiting Professor Dr. Tom Kozo. Her research interested me because the theories she applied required a great deal more data to support a model of the system. Also, the project would involve and incorporate many facets of oceanography including physical oceanography, biological oceanography, hydrography, remote sensing, physical and numerical modeling, and meteorology.

One of the biggest hindrances to this process has been the very limited amount of data that have been collected for this region southwest of Iceland. As a result, my project became primarily analytical in nature. This project could still be further developed with significant work on creating a local numerical model. This was not yet possible given the limited amount of data support available. Almost all of the hydrographic data that were collected had to be extracted from files and graphs, and maps needed to be plotted first.

A number of people have assisted me on this project since I began it over a year ago. I thank those that have provided time, data, and thoughts to this research effort. I would especially like to acknowledge Dr. Ken Brink for all the initial help and focus of my research this past summer at Woods Hole; in particular he suggested that thorough documentation of the upwelling, rather than modelling, would prove more fruitful at this time. Also, thanks to Mr. Will Gould of NOAA-NESDIS for help in obtaining satellite AVHRR data. I am thankful for the professional courtesy and suggestions received at the American Geophysical Union meetings where I presented preliminary results of this research project. And finally, I am indebted to Assistant Professor Peter Guth, whose countless hours and considerable patience contributed to the success of this Trident project.

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APPENDIX A. National Ocean Survey Data

One of the primary objectives of this research project has been to thoroughly document the observed upwelling feature off the southwest coast of Iceland. Data were obtained from a number of sources. Most of the sources of previous work conducted by the Icelanders, along with a number of the atlases and charts of wind and current patterns, were uncovered at the Woods Hole Oceanographic Institution. Unfortunately, few plotted maps of sea-surface temperature could be found. Consequently, two different sets of data were obtained from the National Oceanographic Data Center (NODC). The NODC is the U.S.'s national center which acquires, processes, stores and disseminates global oceanographic data. This research utilized oceanographic station data obtained from both mechanical bathythermograph (MBT), and the expendable bathythermograph (XBT) which has now replaced the MBT.

Digitized station data were processed onto magnetic tape and received on floppy disks (Kidwell, 1986). A Pascal program was then written to extract the necessary information needed to develop monthly SST maps. The MicroDEM program was then used to map the bathymetry of the Iceland area prior to plotting the temperature isotherms (Guth, 1989; Guth and others, 1987). MicroDEM manipulates digital elevation models to produce contour maps and topographic profiles. Digital Elevation Data with a 5 arc minute spacing from the ETOPO5 data set, available from the National Geophysical Data Center in Boulder, Colorado (Hittleman and others, 1989), was used in order to plot the bathymetry for Iceland and the surrounding waters.

I wrote the following Pascal program which reads the raw data obtained on floppy disk. It then sorts it and stores it according to month, allowing the data to be in a form easily plotted as sea surface temperatures.

```
Program ReadNOSdata; {Sorts and Stores data according to month 2/26/90}

Uses
   DOS,Crt;

var
   Int,Choice : integer;
   ContInd,Bl : string[1];
   DegStr,
   Country    : string[2];
   DegStr2,
   MinStr,
   MinStr2,
   Bl3        : string[3];
   junk       : string[23];
   date,
   junk6      : string[6];
   junk14     : string[14];
   junk15     : string[15];
   time       : string[3];
   Bl2        : string[1];
   junk3      : string[3];
   morejnk    : string[20];
   junk48     : string[48];
   obsdepth,
   temp,
   salinity,
   sndspd,
   stddepth,
   stdspd     : string[5];
   mindepth,
   maxdepth,
   depthdiff,
   sigmat,
   stdtemp,
   stdsalin,
```

```
  stdsigma   : string[4];
  sampintr,
  wavedir,
  winddir,
  windspd,
  weather    : string[2];
  saln, O2   : string[1];
  tfile      : text;
  code       : integer;
  Deg,
  Min,
  Deg2,
  Min2       : real;
  LongString : string[255];
  i          : INTEGER;

  file1,file2,file3,file4,file5,file6 : Text;
  file7,file8,file9,file10,file11,file12 : Text;


Procedure WriteFile(Var OutFile : Text);
Begin
  writeln(OutFile, ContInd,Bl,Country);
  writeln(OutFile, deg:12:0,Min:12:2);
  writeln(OutFile, Deg2:12:0,Min2:12:2);
  writeln(OutFile, date,' ',time,' ',mindepth,' ',maxdepth);
  writeln(OutFile, depthdiff,' ',sampintr,' ',Bl,saln,' ',O2);
  writeln(OutFile, wavedir,' ',winddir,' ',windspd, ' ',weather);
  writeln(OutFile, obsdepth,' ',temp,' ',salinity,' ',sigmat,' ',Bl,sndspd);
  writeln(OutFile, stddepth,' ',stdtemp,' ',stdsalin,' ',stdsigma,' ',stdspd);
end;


begin
   TextColor(Yellow);
   ClrScr;
   writeln('Converting data according to month');
   writeln;

   assign(tfile,'c:od.1');
   reset(tfile);

   Assign(File1, 'Jan');
   Assign(File2, 'Feb');
   Assign(File3, 'Mar');
   Assign(File4, 'Apr');
   Assign(File5, 'May');
   Assign(File6, 'Jun');
   Assign(File7, 'Jul');
   Assign(File8, 'Aug');
   Assign(File9, 'Sep');
   Assign(File10, 'Oct');
   Assign(File11, 'Nov');
   Assign(File12, 'Dec');
```

```
Rewrite(File1);
Rewrite(File2);
Rewrite(File3);
Rewrite(File4);
Rewrite(File5);
Rewrite(File6);
Rewrite(File7);
Rewrite(File8);
Rewrite(File9);
Rewrite(File10);
Rewrite(File11);
Rewrite(File12);

while not EOF(tfile) do begin
   read(tfile,ContInd,Bl,Country,junk);
   read(tfile,DegStr,MinStr);
   val(DegStr,Deg,code);
   if MinStr[3] = ' ' then begin
       Delete(MinStr,3,1);
       val(MinStr,Min,code);
     end
   else begin
      val(MinStr,Min,code);
      Min := 0.1 * MIn;
   end;
   read(tfile,Bl2);
   read(tfile,DegStr2,MinStr2);
   if MinStr2[3] = ' ' then begin
      Delete(MinStr2,3,1);
      val(MinStr2,Min2,code);
   end
   else begin
      val(MinStr2,Min2,code);
      Min2 := 0.1 * MIn2;
   end;
   val(DegStr2,Deg2,code);
   read(tfile,Bl2,date,time,junk6,junk15,mindepth, maxdepth,junk3);
   read(tfile,depthdiff,sampintr,Bl,saln,O2,morejnk);
   read(tfile,wavedir,junk6,winddir,windspd,junk15,weather,morejnk);
   read(tfile,obsdepth,Bl3,temp,Bl2,salinity,Bl3,sigmat,Bl,sndspd,junk48);
   readln(tfile,stddepth,Bl3,stdtemp,junk3,stdsalin,junk3,stdsigma,Bl,stdspd,junk48);

   Val(copy(Date,3,2),Choice,int);
   case Choice of
        1 : Begin
               Writeln('Writing to file JAN');
               WriteFile(File1);
            end;
        2 : Begin
               Writeln('Writing to file FEB');
              WriteFile(File2);
            end;
        3 : Begin
```

```
              Writeln('Writing to file MAR');
              WriteFile(File3);
           end;
        4 : Begin
              Writeln('Writing to file APR');
              WriteFile(File4);
           end;
        5 : Begin
              Writeln('Writing to file MAY');
              WriteFile(File5);
           end;
        6 : Begin
              Writeln('Writing to file JUN');
              WriteFile(File6);
           end;
        7 : Begin
              Writeln('Writing to file JUL');
              WriteFile(File7);
           end;
        8 : Begin
              Writeln('Writing to file AUG');
              WriteFile(File8);
           end;
        9 : Begin
              Writeln('Writing to file SEP');
              WriteFile(File9);
            end;
        10 : Begin
                Writeln('Writing to file OCT');
              WriteFile(File10);
            end;
        11 : Begin
              Writeln('Writing to file NOV');
              WriteFile(File11);
            end;
        12 : Begin;
              Writeln('Writing to file DEC');
              WriteFile(File12);
           end;
   end (case);

end (while);

close(File1);
close(File2);
close(File3);
close(File4);
close(File5);
close(File6);
close(File7);
close(File8);
close(File9);
close(File10);
close(File11);
```

```
   close(File12);

   Writeln('Finished converting data.');
   Writeln;
   Readln;
end.
```

APPENDIX B. Manipulation of AVHRR Data

Satellite imagery also aided in documentation of the upwelling. AVHRR images from NOAA-NESDIS were acquired to analyze sea-surface temperature variability observed from space. After negatives of cloud-free images of Global Area Coverage (GAC) data were selected, the desired scenes were transferred to a magnetic tape format. The tape was then processed on a Digital Image Processing System (DIPS) to produce the final images. Scenes with cloud-free images of the area under investigation were processed to produce maps of sea surface temperatures for different time periods. This was accomplished in the following manner. First the cloud-free images were compiled on tape to be processed by the DIPS. Once the proper algorithms and filters were applied to the images, color prints of the adjacent waters of the Iceland coast were developed. The color changes represent the change of sea-surface temperatures. The warmer surface waters are represented by the brighter colors (red, orange, yellow) while the blue, purple, and green signify a colder water intrusion.